Proceedings of the 3rd IASME/WSEAS International Conference on Geology and Seismology (GES'09), pp. 36-40

Geosystemics

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Abstract: - For Geosystemics we define the science that studies the Earth system from a holistic point of view. Earth is thus considered as a whole and unique far-from-the equilibrium complex system, formed by numerous different parts (sub-systems), which do not act independently but interact each other continuously. Most interactions are nonlinear, so that we can usually say that "resultant is more than the sum of the parts". Interactions are not only in terms of contrasts but, and mostly, cooperative and mutual organizations. We will see some aspects and properties of this approach with a few examples.
Key-Words: - Geosytemics, Earth system, Nonlinear Analysis, Entropy, Geophysics

1 Introduction

The world is far more complex than we can idealise. Nevertheless, we always try to represent it with our models. Introducing a model we must define also its limits: all models have some limits, i.e. they are only a partial representation of reality. As soon as our models become more complex, we realise that not only the parts of the model must be consistent with the true parts of reality, but also, and mostly more important, the interconnections among the parts must be as close as possible to the real interconnections of parts forming a real system. When the real system is the Earth, we cope with the largest system in the planet, i.e. the planet itself, so that complexity grows up almost indefinitely. In many aspects this resembles the Gaia theory [1], where the main elements of the Earth system are complex systems themselves: biota, oceans, geosphere and atmosphere, with continuous couplings, exchanges, interactions and interplaying amongst each other, and even amongst their own sub-systems and sub-elements. These are the reasons why it is often much easier to consider the Earth in its whole integrity, from a holistic viewpoint. We define Geosystemics as *the science that studies the Earth system from a holistic point of view*. Earth is thus considered as a whole and unique far-from-the equilibrium complex system, formed by numerous different parts (sub-systems), which do not act independently but interact each other continuously. Most interactions are nonlinear, so that we can usually say that "resultant is more than the sum of the parts". This aspect is typical of chaos: this discipline is funded on those nonlinear processes which are characterised by sensitivity to initial conditions: their phase space is so fuzzy and irregular (in one word, it is *fractal*; see section 4) that even two points which are very close in a certain time finally diverge, as time flows. Interactions are not only in terms of contrasts but, and mostly, cooperations and mutual organizations. In this short paper, we will illustrate some important aspects related to Geosystemics and clarify some concepts with a few examples.

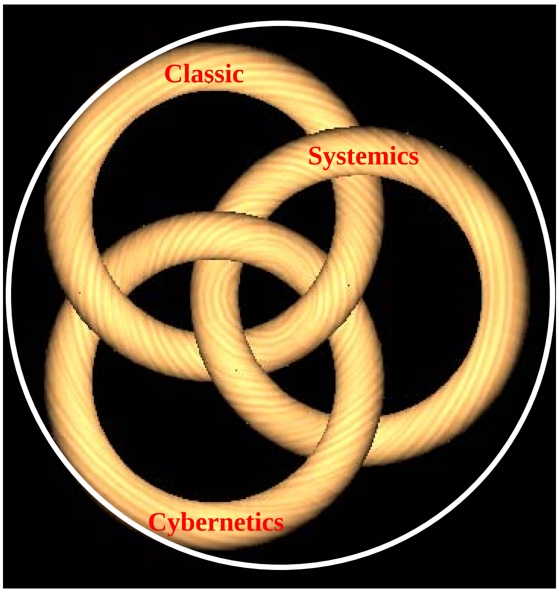


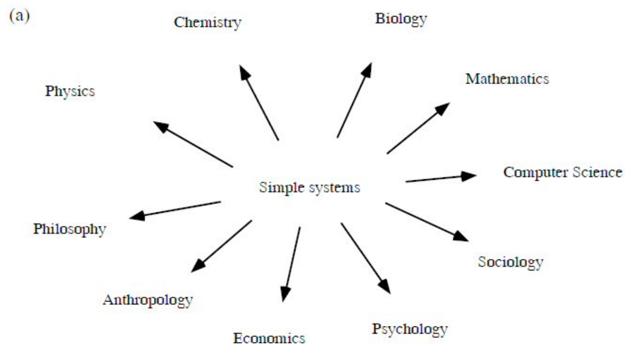
Fig.1 Borromean rings illustrate the inter-connected importance among classic disciplines, Cybernetics, and Systemics (adapted from ©Creative Commons). The larger circle mimics the superior integration of the three rings made by Geosystemics.

ISSN: 1790-2769 ISBN: 978-960-474-058-1

2 Geosystemics Formulation

To provide another simple definition of Geosystemics we can also formulate it as a superior integration of the combination of classic disciplines, such as Physics, Mathematics, Chemistry, Biology, including some Geo-sciences, like Geology, Geophysics, Geochemistry, with some more recent ones, like Systemics [2,3] and Cybernetics [4,5]. Fig.1 shows an ideal representation by means of *Borromean rings*: each one identifies a discipline or a series of disciplines. The Borromean rings tell us that each ring is as necessary as the others.

The importance of Cybernetics for Geosystemics is evident if we bear its definition in mind: it is the interdisciplinary study of the structure of regulatory systems. Thus since Earth possesses feedback elements, they can be thought as regulatory systems.



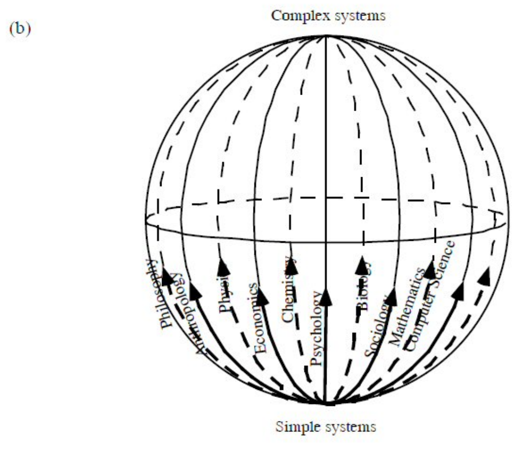


Fig.2 Conceptual figures for Simple (a) and Complex (b) systems (from [2]).

Geosystemics relates with Earth as a complex system. A simple conceptual comparison between simple and complex systems is shown in Fig.2. We now need to define what a complex system is and, at the same time, we have to adapt this definition in the context of Earth. To perform this difficult task, we can help us with a step by step general definition [6] written in *italics* to which we will add some specific considerations valid for Earth:

1. *a complex system contains many constituents interacting nonlinearly,*
2. *and interdependent;*

This is the specific case of our planet, composed by an enormous number of sub-systems and elements and sub-elements, placed into around 10^{12} km^3 of solid volume and much more larger volume of its biosphere and gaseous atmosphere.

3. *A complex system possesses a structure spanning several scales.*

Earth phenomena range from atomic scale to thousands - km scale, from almost instant processes to billion – year timescale;

4. *and it is capable of emerging behaviour.*

Here we mean "some *new* emerging behaviour", that is a different behaviour than the usual of the past. This item is also related to the concept of *surprise*, as well as to some other interesting properties, such as the *capability of change*, in its numerous aspects and facets: the property of self-reproduction (*autopoiesis*), that, together with *mixing*, is as fundamental as ubiquitous in the Earth. In fact, we find reproducing living organisms, but also what is apparently inanimate such as the terrestrial oceanic and continental lithosphere, which is part of an endless cycle of generation/ evolution/ death, i.e. the so-called Wilson cycle of plate tectonics [7] or an even more complex cybertectonics of Earth [8]. Also the apparently simple game of life [9], which is simple in terms of rules but complex in behaviour, is based on the capability of self-reproduction.

Finally we mention the last two points:

5. *It is characterised by an interplay between chaos and non-chaos,*

For comparison, inter-relations among chaos, complexity and entropy, please refer to [6]. This point indicates that chaos can emerge sporadically, due to some change of the boundary conditions under which the phenomenon is occurring.

6. *and between cooperation and competition.*

The last point can be interpreted with the presence of some *feedback* among parts of the complex system. Feedback could be positive or negative, at different time, involving cooperation or competition in the same system. Factors can emerge to balance opposing situations in order to get the system more stable than expected: this is just the case of Earth, where even in presence of an overwhelming polluting human species, producing so much disturbing effects over the planetary system, Earth itself attempts to self-organise in

order to counterbalance the negative effects. Feedback loops will then appear to keep the planet in balance: this is the most striking feature of Gaia theory [1].
Other important concepts can be assessed and applied to Earth system [10-12] but that we do not mention here.

3 The New Geophysics

In this prospect, Geosystemics can be considered the ensemble inter-collection of a series of new approaches in Science and in Earth Science, in particular: Chaos, Complexity [6], nonlinearity, Self-organised Criticality [13], Synergetics [14], Enformy [15], and something closer to geosciences as New Geophysics [16-18].
The latter, for example, is a new understanding of fluid-rock deformation in the crust, where fluid-saturated microcracks are so closely spaced that they verge on fracture-criticality and failure in fracturing and earthquakes, and are critical systems. As a critical system, the crust has fundamental new properties and may be considered as a New Geophysics with subtle implications for much of the behaviour of solid-earth geoscience [16-18].

4 Fractal dimension, degrees of freedom and Shannon Entropy

When we deal with complex systems is fundamental to use *universal* physical quantities. This is also the case of Earth. To this aim we recall some of these quantities: fractal dimension [e.g. 19], degrees of freedom and (information) entropy [20].
In a fractal ensemble with N=N(ε) elements with size ε, the fractal dimension D is defined as [19]:

$$D = \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log 1/\varepsilon} \qquad (1)$$

Fig.3 shows an example of fractal interpretation that has been given for the core-mantle boundary of Earth, from the study of the geomagnetic field over the last 400 years [21].
The phase space of a dynamical system is the ideal space where each state of the system can be represented by a single point [22]. The minimum number *E* of phase space axes, which contain all orbits of the dynamics, defines the degrees of freedom of the system, i.e. the number of variables that are required to describe that system. E is also said embedding dimension [19].
Fractal dimension in time or space of a given process of Earth provides important clues about its history and dynamics. Degrees of freedom can help in finding the correct dynamical equations which govern the evolution of the system.

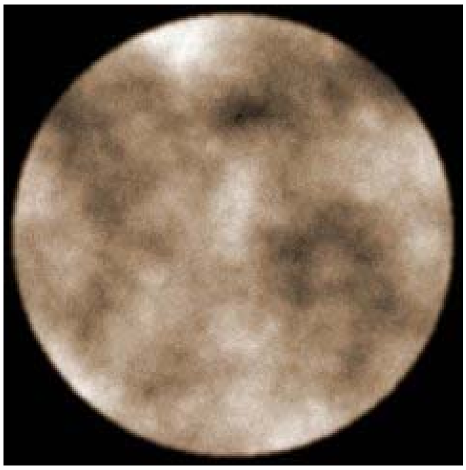


Fig.3 A possible aspect of the core-mantle boundary as a fractal surface with D=2.2 [21].

Information theory [20] provides essential universal tools to interpret and "measure" complex systems and their relationship with an observer, with the great goal to distinguish the real message of the system from the influence of system's environment (Fig.4).

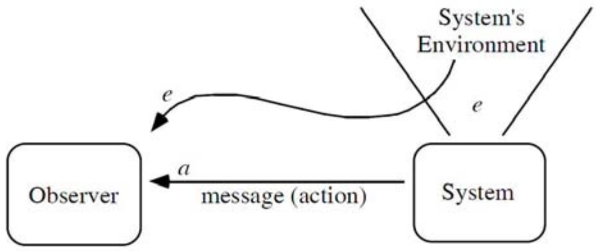


Fig.4 What an Observer measures is the message from the System under study (action *a*) plus some influence from its environment (signal *e*) (from [2]).

The Shannon information *I*(*t*) of a quantity B(t) defined over a sphere as an expansion of a truncated series of orthonormal spherical harmonics Ψ_n with maximum degree *N*, can be defined as:

$$I(t) = \sum_{n=1}^{N} p_n(t) \cdot \ln p_n(t) \qquad (2)$$

where $p_n(t)$ is the probability to have a certain *n*-degree spherical harmonic *power* contribution instead of another [23]:

ISSN: 1790-2769 ISBN: 978-960-474-058-1

$$p_n = \frac{\langle B_n^2 \rangle}{\langle B^2 \rangle} = \frac{\sum_{m=0}^{n} (c_n^m)^2}{\sum_{n'=1}^{N} \sum_{m=0}^{n'} (c_{n'}^m)^2} \qquad (3)$$

with $\sum_n p_n = 1$, and $p_n \ln p_n = 0$ if $p_n = 0$; c_n^m are the spherical harmonic coefficients; triangular brackets stand for mean square values, i.e. a sort of average power of B. Then Shannon Entropy, H, can be defined as simply as $H = -I$. We can also define normalised information or entropy dividing by $\log N$, which is the maximum entropy for a system whose N states have all the same probability distribution $p_n = 1/N$. This kind of entropy is *configurational* and provides a measure the degree of disorder of a spatial system that changes in time. Alternative formulations of Shannon entropy can be found in literature [e.g. 24]. Formulations (2) and (3) can be applied to any function defined over a sphere, in particular over the Earth. In geomagnetism we can apply a definition slightly different from (3) to geomagnetic field [22] expressed with Schmidt quasi-normalised spherical harmonics so that $p_n(t)$ can be interpreted as the n-th contribution at time t to total energy $\langle B^2 \rangle$ of the magnetic field of the Earth from *all* $n \cdot (n+2)$ components of degree n [23, 25].

An analogous approach has been applied to magnetic data from low earth orbiting satellite with the objective of detecting possible electromagnetic signatures due to big earthquakes with interesting results [26].

5 Mutual and transfer information

Geosystemics is based on the importance of the inter-relations among the components which form the terrestrial complex system. For this reason every quantity that measures these inter-relations is important. Instead of linear quantities such as correlation coefficient or cross-correlation function between two variables belonging to linear processes, we have to resort to statistical quantities which are more useful for nonlinear processes, as typical in a complex system.

Given two variables X and Y, characterising two processes of the phenomenon under study, we define the mutual information I(X,Y) extending definition (2) to two variables, i.e.:

$$I(\mathrm{X};Y) = \sum_{y \in Y} \sum_{x \in X} p\ (x,y) \cdot \ln\left(\frac{p(x,y)}{p_1(x)\, p_2(y)}\right) \qquad (4)$$

where $p_1(x)$ and $p_2(y)$ are the corresponding probabilities and $p(x,y)$ is the joint probability.

However this formulation does not say anything about the direction of information transfer, between process X and process Y, i.e. from a part of a system to another. For this purpose, it is possible to introduce a useful definition that quantifies the information flow in terms of the Kullback entropy [27], which can be defined for a single process X as:

$$K_x = \sum_x p(x) \cdot \ln[p(x)/q(x)] \qquad (5)$$

The above quantity is the entropy related to the process X when a different probability $q(x)$ is used instead of the true $p(x)$.

Here, we do not describe more details but we just want to emphasise the importance of quantifying direction of information flow amongst different parts or processes of the system under study, because often is more important to know where the flow of information is going instead of just estimating the information of the whole process [28].

6 Discussion and conclusions

In this short paper I have introduced Geosystemics. This new approach includes some already introduced concepts and categorise some nonlinear universal tools, such as fractal dimension, phase space, degrees of freedom and Shannon information and entropy. Geosystemics' objective is the formalization of geosciences from a holistic viewpoint. Complexity, irreversibility, criticality, nonlinearity, self-organisation, just to mention some, become the main foundations upon which we can establish the investigation of our planet and the complex interactions among its parts: without interactions Earth would be death. Geosytemics concentrates in the interactions among parts of Earth in order to understand the whole system.

Acknowledgements

A grateful thank to G. Cianchini, G. Gregori and L. Qamili for their valuable suggestions and useful discussions. Part of this work has been supported by the project REM of PNRA.

References:

[1] Lovelock J. (2001), *Homage to Gaia: The Life of an Independent Scientist,* Oxford University Press.

[2] Bar-Yam, Y. (1997) *Dynamics of Complex System*, Addison-Wesley, Reading.

ISSN: 1790-2769 ISBN: 978-960-474-058-1

[3] Bunge M. (1979). *A world of systems*. Dordrecht ; Boston, Reidel.

[4] Wiener N. (1948), *Cybernetics: Or the Control and Communication in the Animal and the Machine.* Cambridge, MA: MIT Press.

[5] François C., (1999) Systemics and Cybernetics in a Historical Perspective, *Syst. Res*., 16, 203-219.

[6] Baranger, M., Chaos, Complexity and Entropy*: a Physics Talk for Non-Physicists*, Wesleyan University Physics Dept. Colloquium (2001).

[7] Gurnis, M. (1988) Large-scale mantle convection and the aggregation and dispersal of supercontinents. *Nature*, 332, 695-699.

[8] Leeder M. (2007), Cybertectonic Earth and Gaia's weak hand: sedimentary geology, sediment cycling and Earth system, *J. Geologic. Soc*., 164, 277-296.

[9] Conway, J. H. (1976). *On Numbers and Game*s, Academic Press, London.

[10] Klir G.J. (1991), *Facets of Systems Scienc*e, Plenum Press, London.

[11] Thom, R. (1972) *Structural Stability and Morphogenesis*, W. A. Benjam.

[12] Wolfram S, (2002) *A new kind of science*, Campaign IL, Wolfram Media.

[13] Bak P. (1996). *How the nature works*, Springer-Verlag, New York.

[14] Haken H. (1977), *Synergetics*, Springer-Verlag, New York.

[15] Watson, D.E. (1993). Enformy: The Capacity to Organize, *Thinking on the Edge*, 181-189, R. Kapnick, A.A. Kelly (Eds), Agamemnon Press, Burbank.

[16] Crampin, S. (2003) The New Geophysics: shear-wave splitting provides a window into the crack-critical rock mass. *The Leading Edge*, 22, 536-549.

[17] Crampin, S., 2006. The New Geophysics: a new understanding of fluid-rock deformation. In Van Cotthem, A., Charlier, R., Thimus, J.-F. and Tshibangu, J.-P. (eds.), *Eurock 2006: Multiphysics coupling and long term behaviour in rock mechanics*. Taylor and Francis, London, 539-544.

[18] Crampin S., Peacock S., (2008) A review of the current understanding of seismic shear-wave splitting in the Earth's crust and common fallacies in interpretation, *Wave Motion*, 45, 675-722.

[19] De Santis A. (1997), A direct divider method for fractal self-affine profiles and surfaces, *Geophysical Research Letters*, vol. 24, No. 16, 2099-2102.

[20] Shannon C. (1948) A mathematical theory of communication, *The Bell Syst. Tech*. J., 27, 379-423, 623-656.

[21] De Santis A., Barraclough D.R., (1997) A fractal interpretation of the topography of the scalar geomagnetic scalar potential at the core-mantle boundary, *Pure and Applied Geophys*., 149, No.4, 747-760.

[22] Gibbs, J. W. (1901) *Elementary Principles in Statistical Mechanic*s. Yale University Press.

[23] De Santis A., Tozzi R., Gaya-Piqué L., (2004) Information Content and K-Entropy of the present geomagnetic field, *Earth Plan. Sci. Lett*.,218, No.3, 269-275.

[24] Van Siclen C. DeW. (1997), Information entropy of complex structures, *Phys. Rev. E*, 56, no.5, 5211-5215.

[25] De Santis A., Qamili E. (2008) Are we going toward a global planetary magnetic change?, *Proceedings of 1st WSEAS International Conference on Environmental and Geological Science and Engineering (EG'08)*, Malta Spt. 2008, 149-152.

[26] Cianchini G., De Santis A., Balasis G., Mandea M., Qamili E. (2009) Entropy based analysis of satellite magnetic data for searching possible e.e. signatures due to big earthquakes, *Proceedings of the 3rd IASME/WSEAS International Conference on Geology and Seismology (GES'09)*, Cambridge, Febr. 2009.

[27] Schreiber T. (2000) Measuring Information transfer, *Phys. Rev. Lett*., 85, No.2, 461-464.

[28] Ahlswede R., Baumer L., Cao N., Aydinian H., Blinovsky V., Deppe C., Mashurian H. (Eds.), (2006) *General Theory of Information transfer and Combinatorics*, Springer-Verlag Berlin Heidelberg.